LLC Resonant Converter

Infineon Technologies

Content

- LLC Topology
  - Benefits and Drawbacks
  - Basic Analysis of LLC Converter
  - Modes of Operation
  - Design
- ICE2HS01G Resonant Mode Controller
  - Key Features
  - Protection
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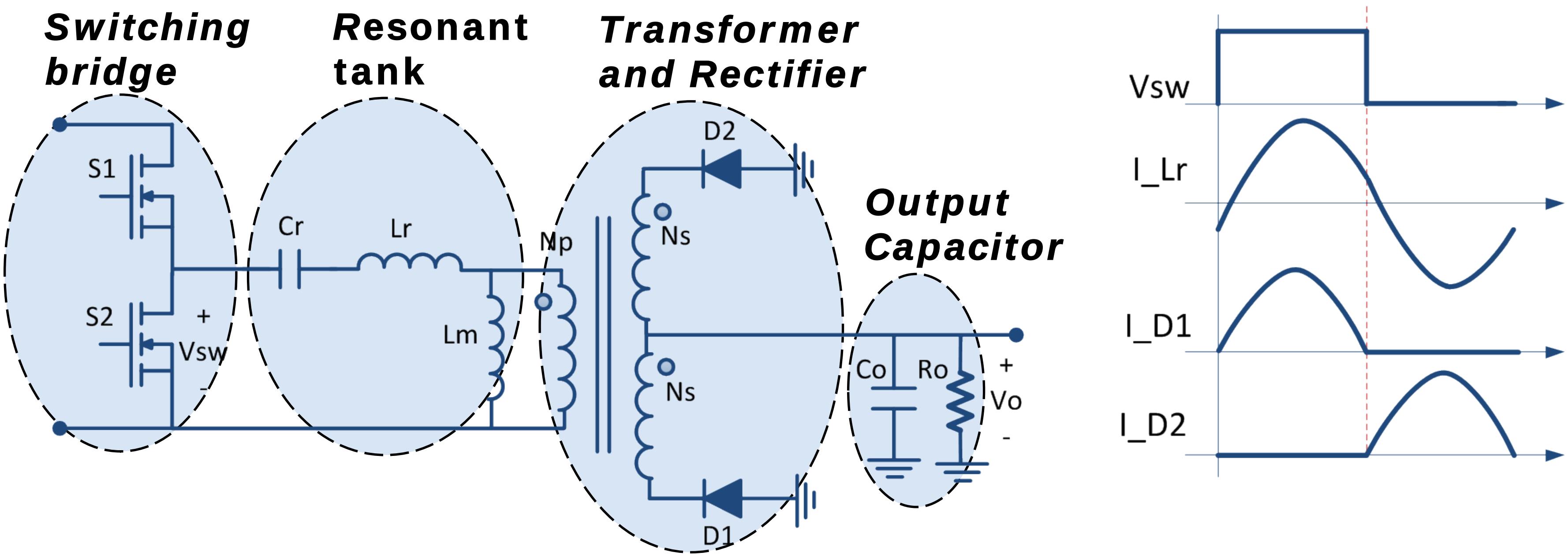
- Reference Designs and Experimental Results
  - Solar LLC Converter
  - SMPS LLC Converter

LLC Benefits and Drawbacks vs. Phase Shift Full Bridge

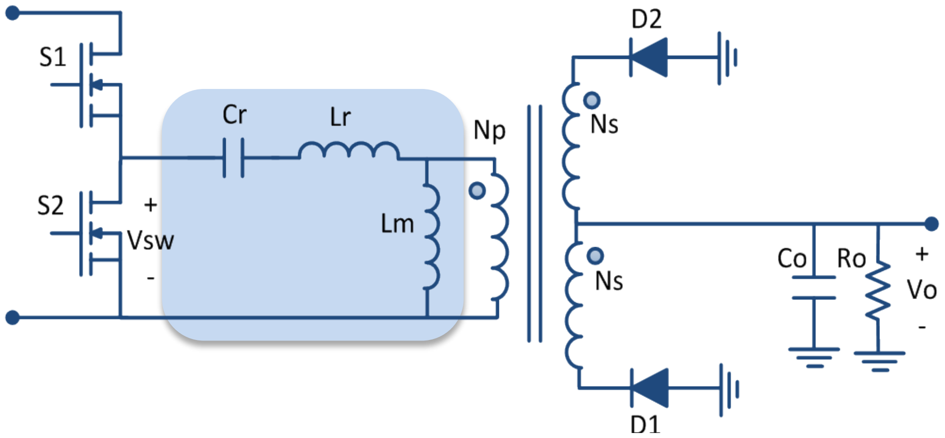
LLC	Phase Shift Full Bridge
Benefits	
Full resonant ➔ less EMI	Quasi resonant
Soft switching in primary and secondary sides ➔ High efficiency	Secondary side is hard switching
Soft switching over a wide load range➔ High efficiency at light load	Soft switching is load dependent
No output inductor ➔ Low BoM cost in magnetics	Needs one or two output inductors
Lower blocking voltage for secondary rectifiers ➔ Lower cost, better FoM devices	Needs higher voltage devices
Half Bridge LLC and Full Bridge LLC covers wide power range applications.	More suitable for high power application
Drawbacks	
More Challenging control and design – knowledge intensive; integrated magnetics require sophisticated design approach	Easy control and straight forward design
Non trapezoidal current waveform ➔ Higher conduction loss overcome by lower Ron FETs, with lower FOM	trapezoidal current waveform ➔ Lower conduction loss
Variable frequency to regulate output voltage	Fixed frequency control

Concept of LLC Resonant Converter

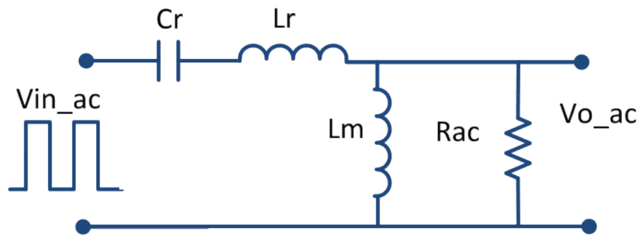


Switching bridge generates square waveform to excite ***resonant tank***, resonant sinusoidal current gets scaled and rectified by ***transformer and rectifier***, ***output capacitor*** filters the ac current to output DC voltage

Basic Analysis of LLC Converter



Equivalent circuit



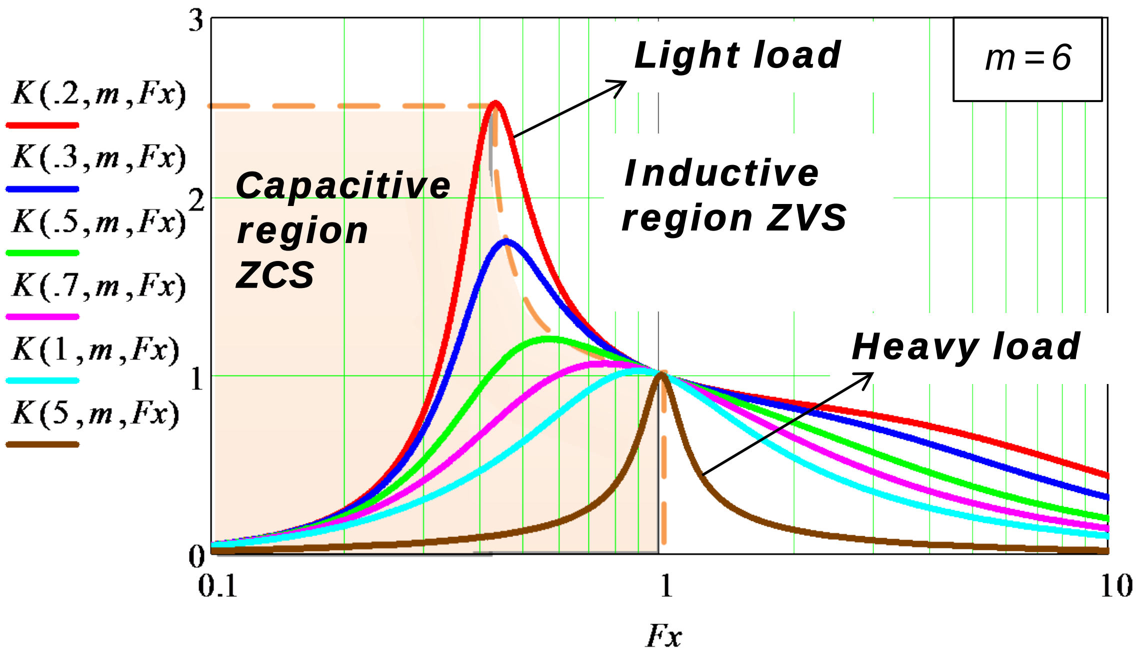
$$K(Q,m,Fx)=\frac{V_{o\_ac}}{V_{in\_ac}}=\frac{Fx^2(m-1)}{\sqrt{\left(m\cdot Fx^2-1\right)^2+Fx^2\cdot\left(Fx^2-1\right)^2\cdot(m-1)^2\cdot Q^2}}$$

$$G=\frac{V_o}{V_{in}}=\frac{1}{2}\cdot K(Q,m,Fx)\cdot\frac{N_s}{N_p}$$

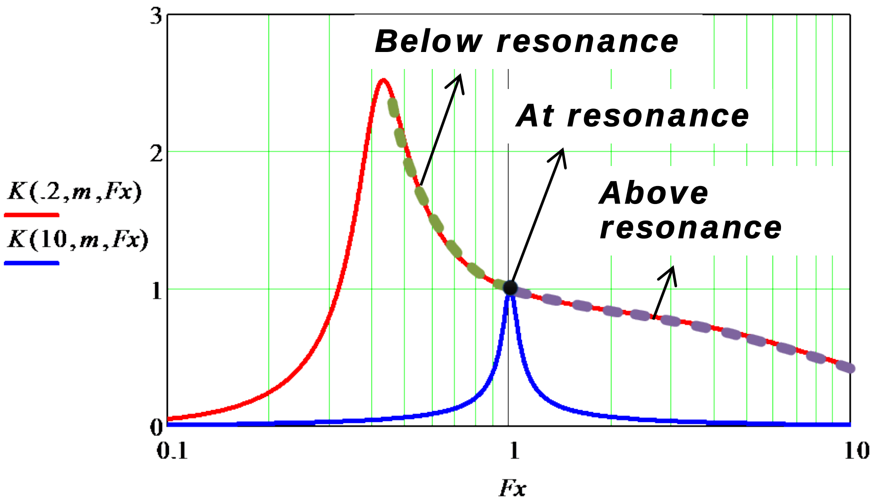
$$Fx=\frac{f_s}{f_r}\qquad f_r=\frac{1}{2\pi\sqrt{L_rC_r}}\qquad Q=\frac{\sqrt{L_r/C_r}}{R_{ac}}\qquad R_{ac}=\frac{8}{\pi^2}\cdot\frac{N_p{}^2}{N_s{}^2}\cdot R_o\qquad m=\frac{L_r+L_m}{L_r}$$

Basic Analysis of LLC Converter

$$K(Q,m,Fx)=\frac{V_{o\_ac}}{V_{in\_ac}}=\frac{Fx^2(m-1)}{\sqrt{(m\cdot Fx^2-1)^2+Fx^2\cdot(Fx^2-1)^2\cdot(m-1)^2\cdot Q^2}}$$

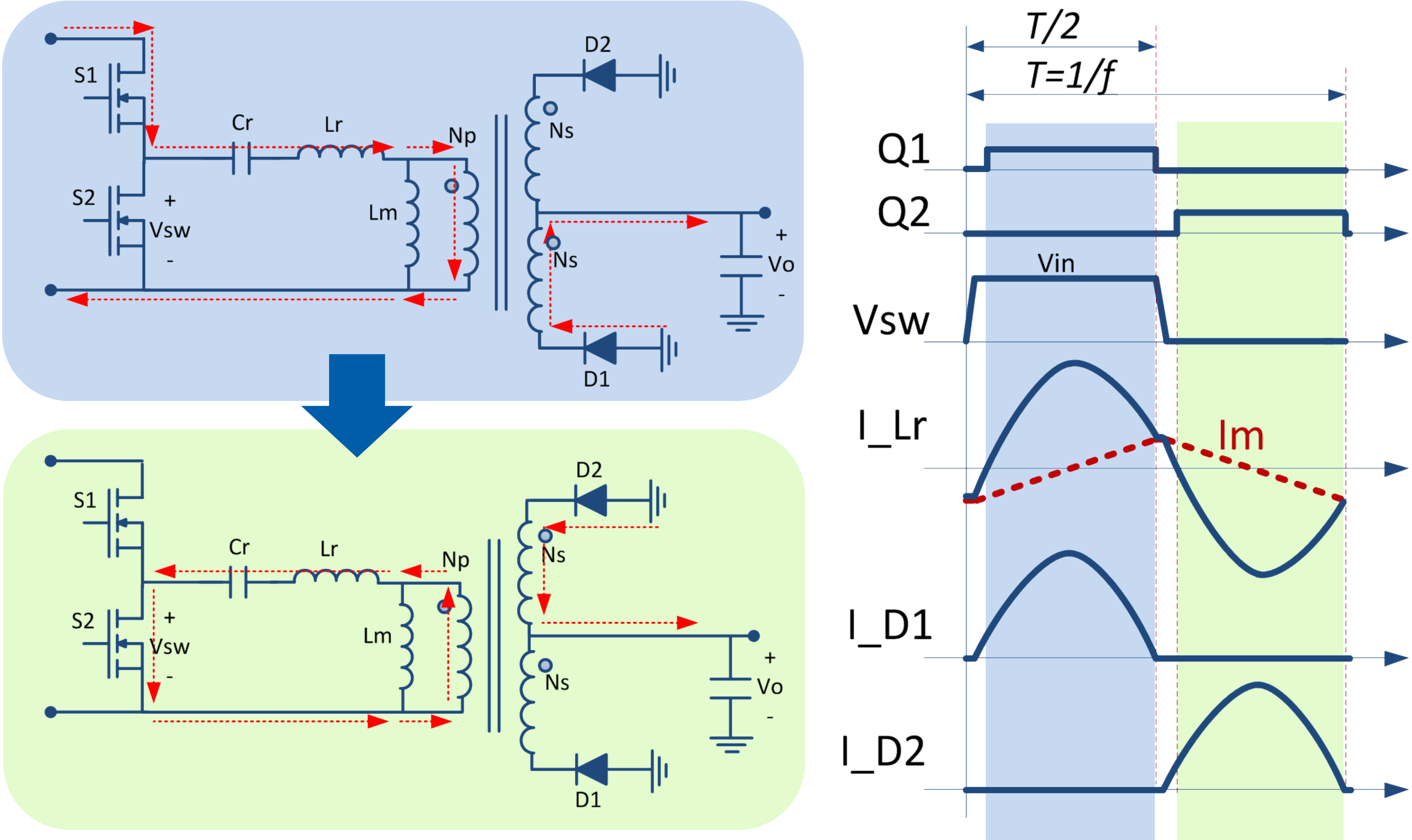


Modes of Operation

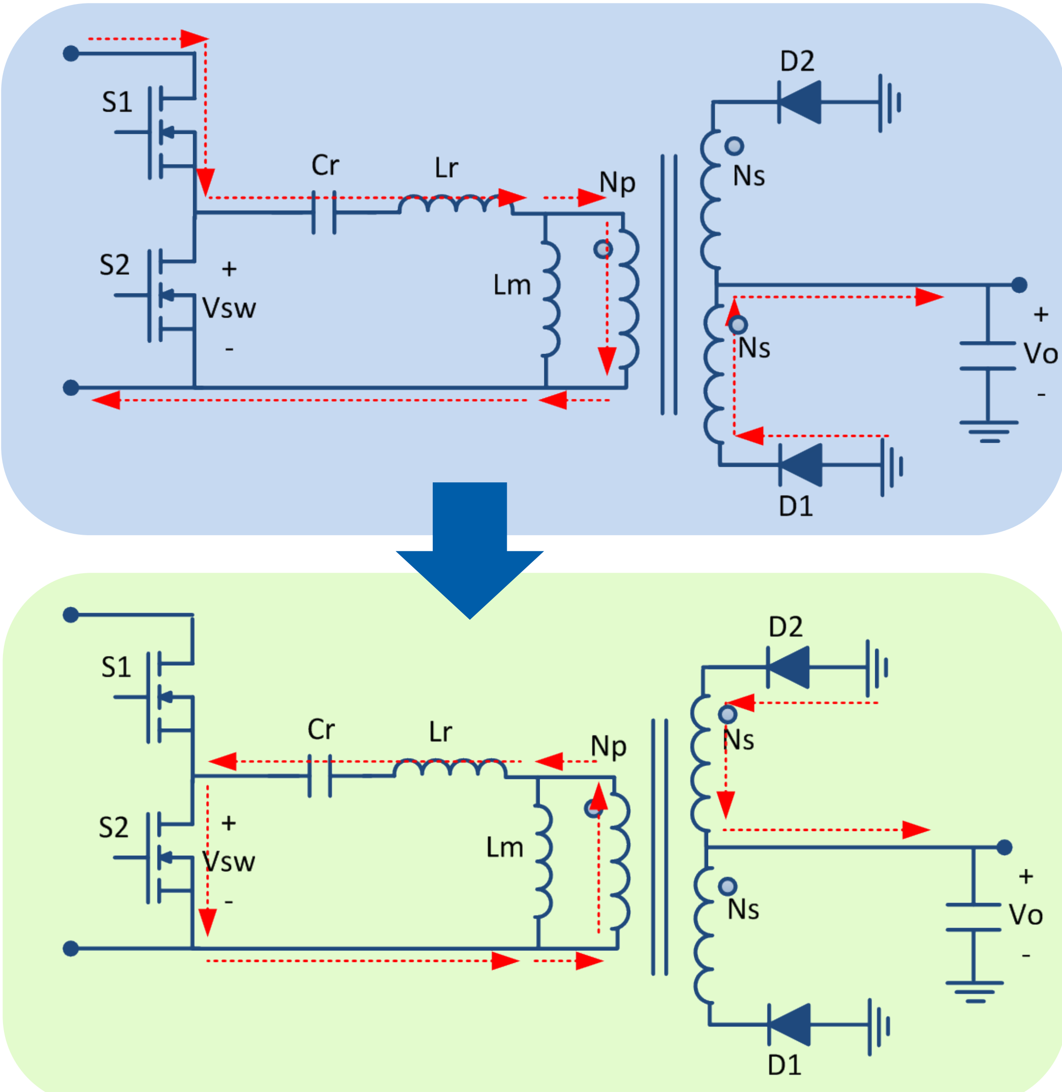


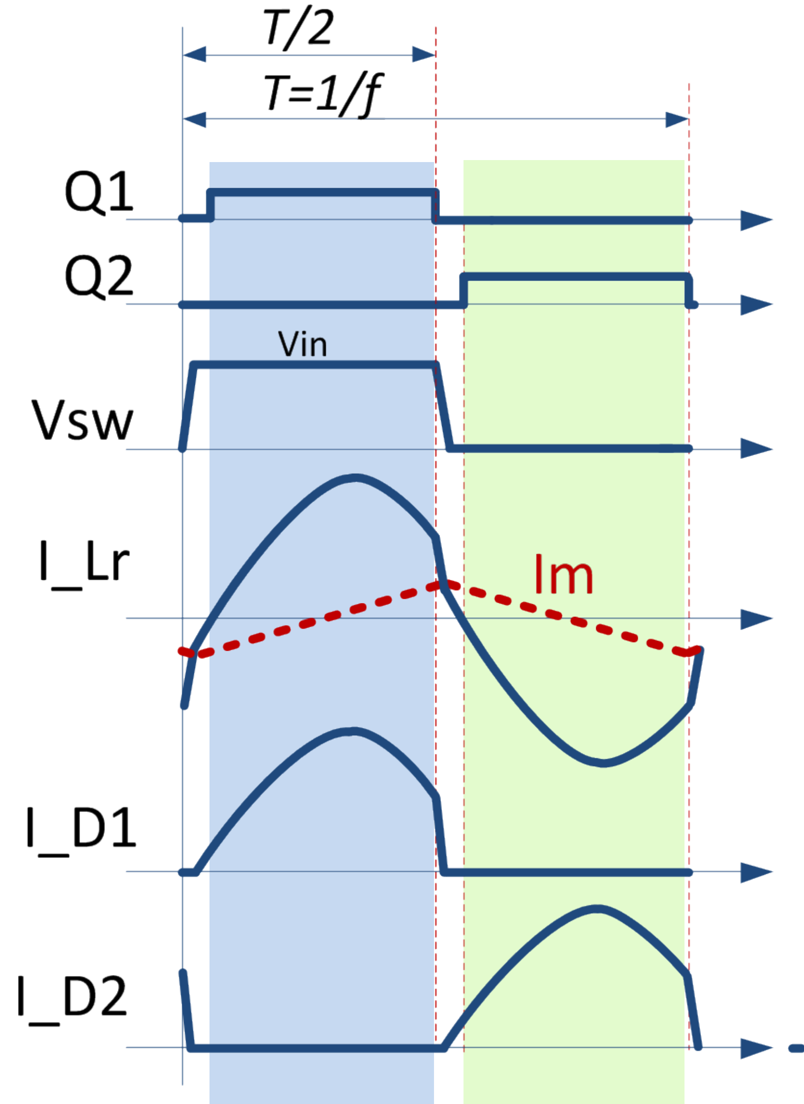
- **At resonance operation fs=fr**
  - Unity gain
  - Optimal operational point
- **Below resonance operation fs<fr**
  - Boost gain
  - Increased primary side conduction losses
  - Has the risk of capacitive mode operation
- **Above resonance operation fs>fr**
  - Buck gain
  - Increased Primary side turn off losses
  - Reverse recovery for secondary side diodes
  - Gain is less sensitive to frequency modulation

At Resonance Operation fs=fr

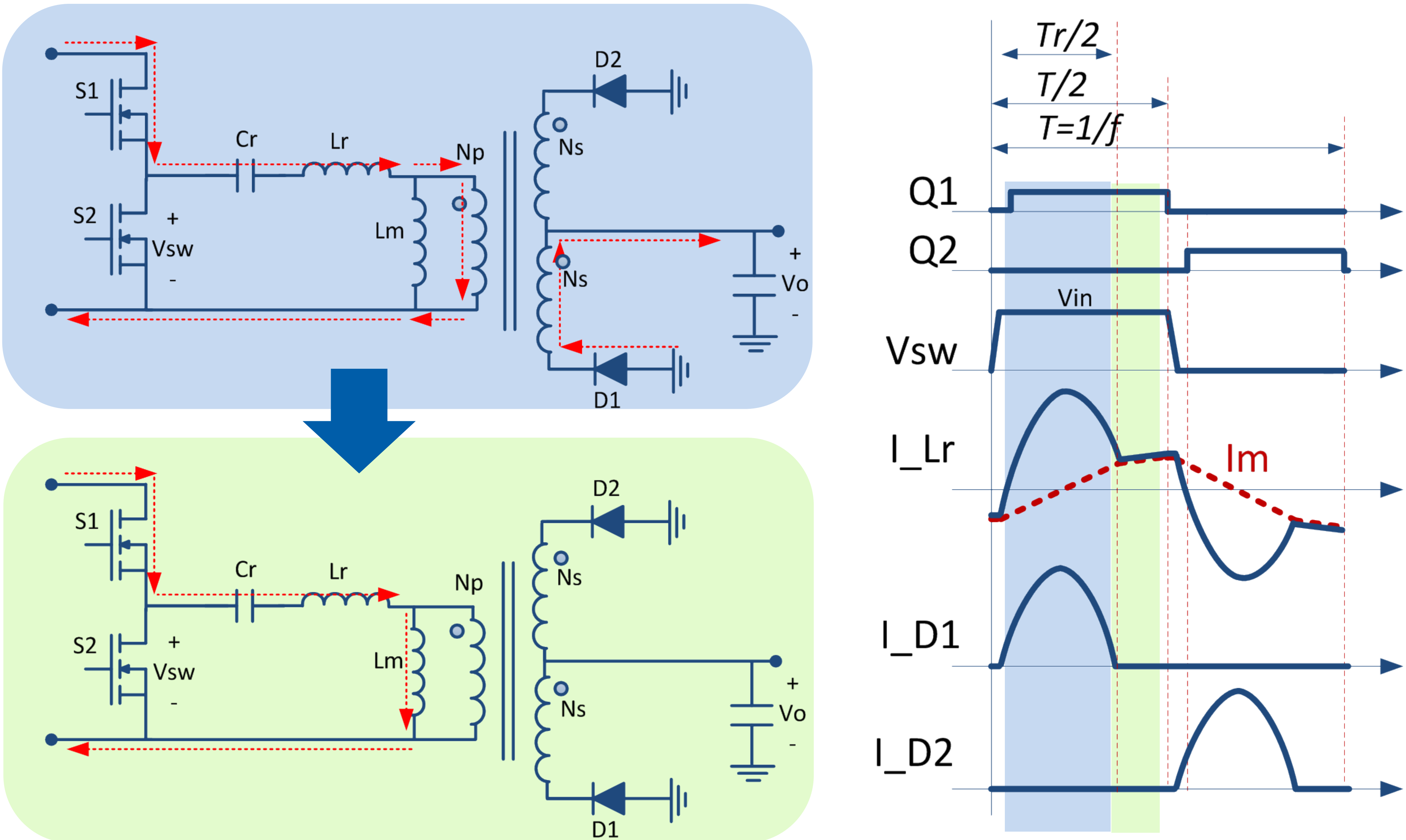


Above Resonance Operation fs>fr

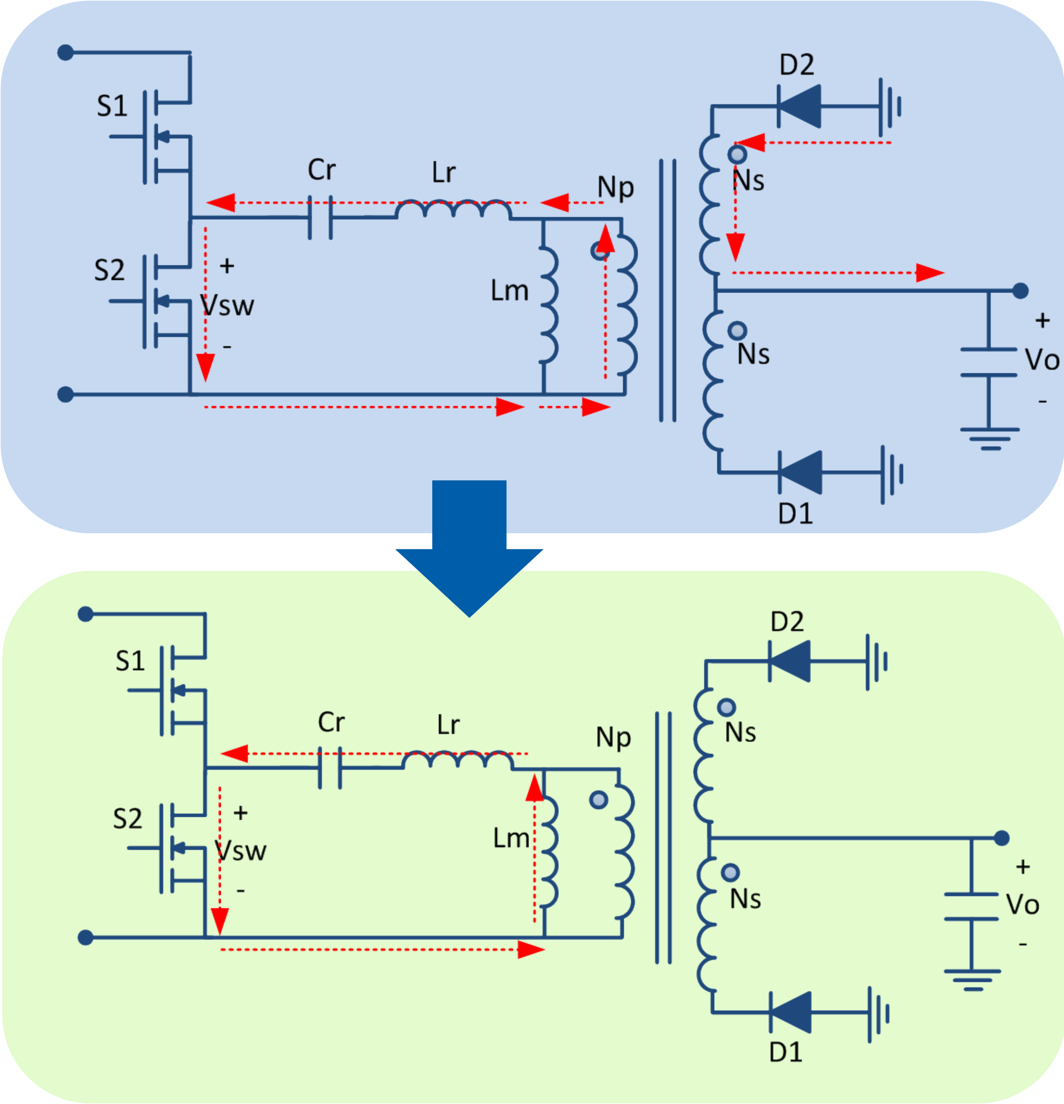


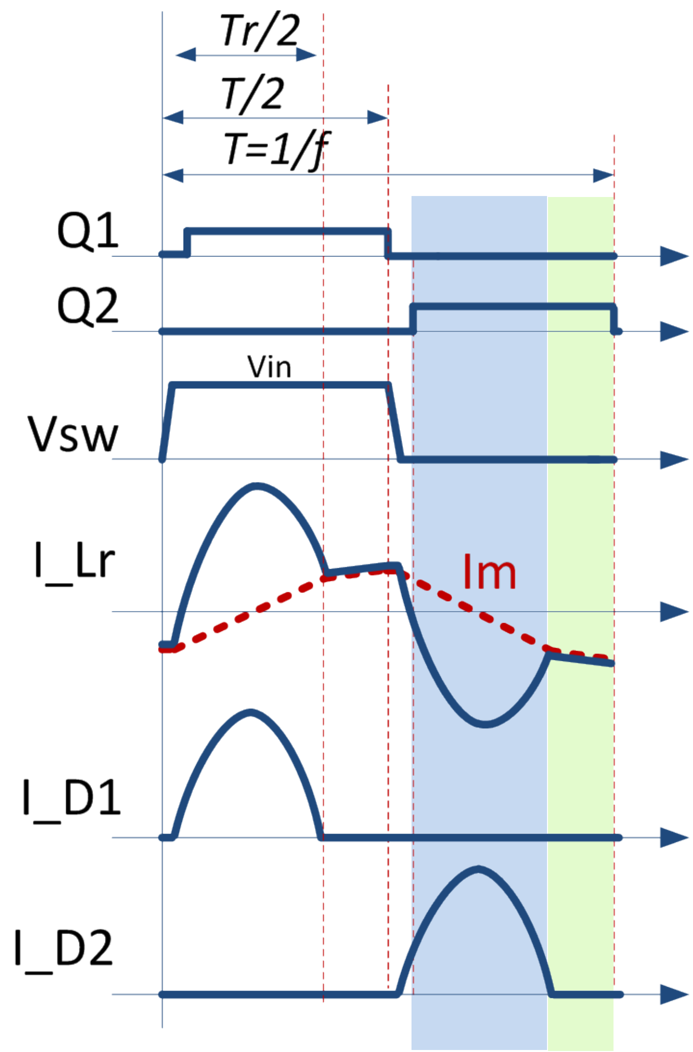


Below Resonance Operation fs<fr

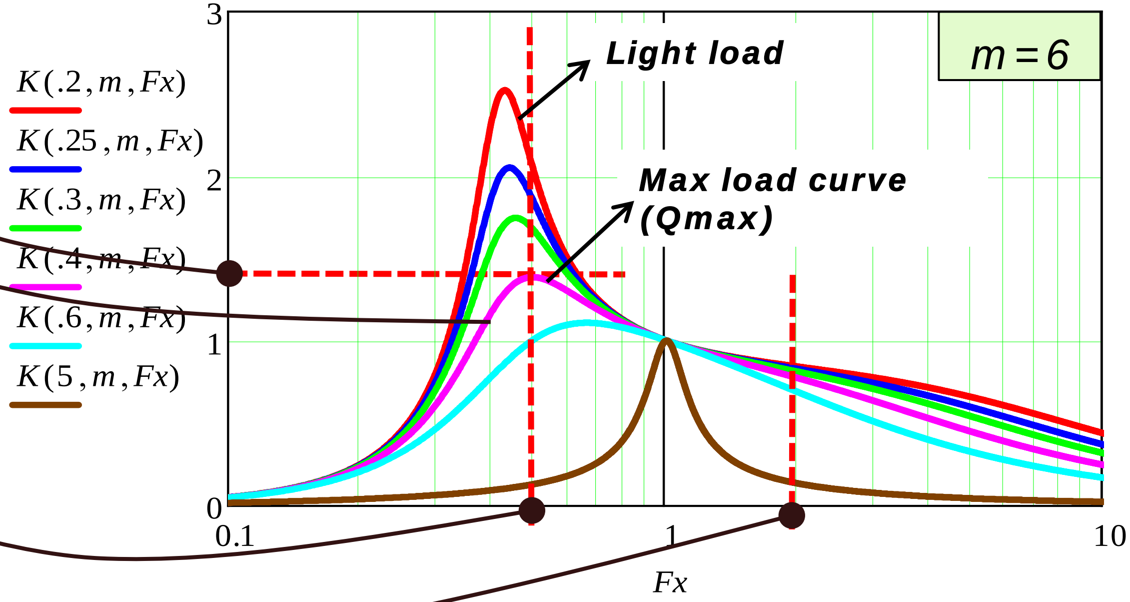


Below Resonance Operation fs<fr





Design Guideline



- Converter's required maximum voltage gain.
- Find which Q curve have that gain at its peak
- The frequency at that peak is set to be the minimum switching frequency.
- Maximum frequency must be limited for high efficiency, pulse skipping is used for further step down gain.

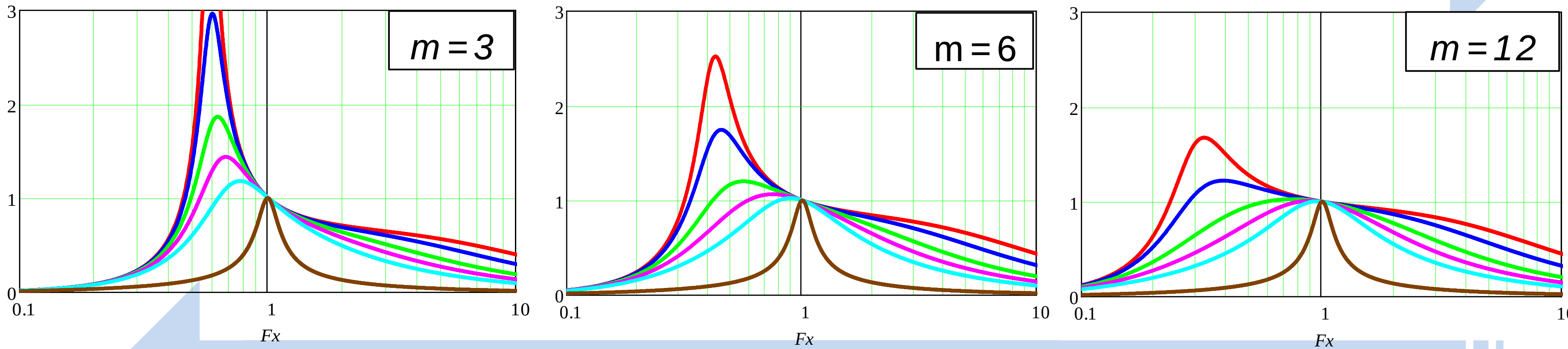
> - Limiting the minimum switching frequency guarantees operating in the inductive region for all load conditions, including and below maximum load.
> - Operation beyond maximum load falls into capacitive region (not safe), which is possible during start up and transient conditions ➔ design must allow some safety margin.

Selection of *m* value

$m=(L_r+L_m)/L_r$

- When choosing m, there is a compromise between input voltage range, efficiency, frequency modulation range, soft switching

Lower magnetizing circulating current ➔ Higher efficiency



Higher boost gain ➔ Wider input range
➔ Narrower frequency range

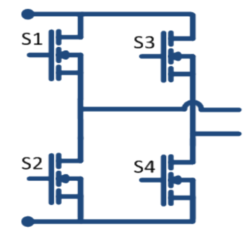
Bridge and Rectifier Selection

Primary Bridge: Half-Bridge compared to Full-Bridge

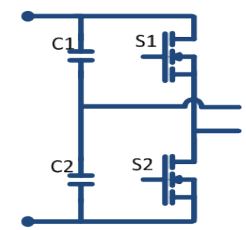
I_{rms}	I_{rms}^2	# of FETs	FETs conduction losses	N_p	R_{pri}	Transformer primary copper loss
× 2	× 4	÷ 2	× 2	÷ 2	÷ 2	× 2

*Comparison assumes same FET and transformer core

Full-Bridge



Half-Bridge

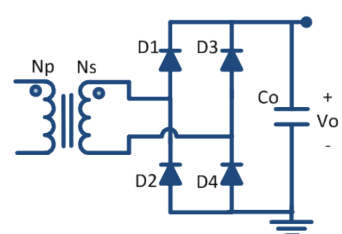


Secondary Rectifier: Full-Wave compared to Full-Bridge

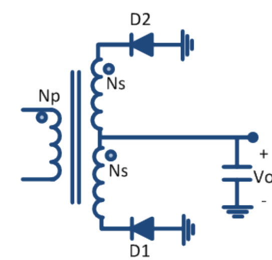
Diode voltage rating	# of diodes	Diode conduction losses	# of secondary windings	R_{sec}	Transformer secondary copper loss
× 2	÷ 2	÷ 2	× 2	× 2	× 2

*Comparison assumes same diode drop and transformer core

Full-Bridge



Full-Wave



ICE2HS01G
Resonant Mode Controller

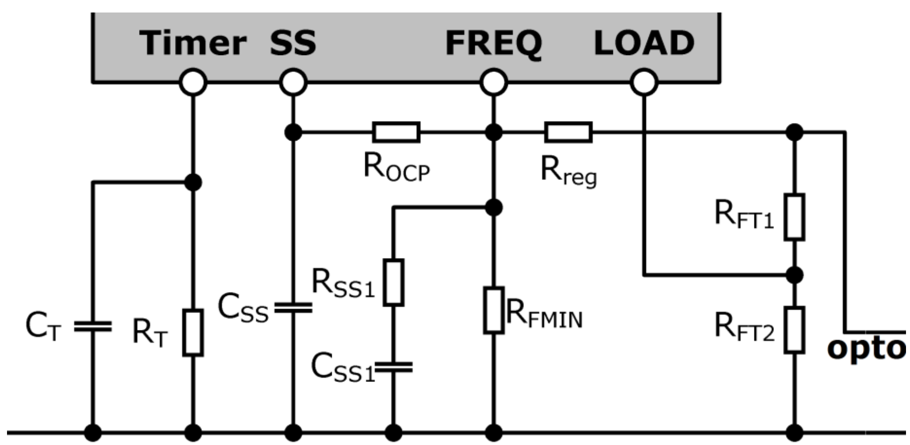
Key Features

- Flexible LLC operation
  - Adjustable frequency for Min, Max, OCP and SS → **Easy design**
  - Maximum switching frequency up to 1MHz → **High power density**
  - Adjustable and adaptive dead time control → **Easy design**
- Novel SR operation mode with various protections (***patent pending***)
  - Can be operated at boost region with SR → **Highest achievable efficiency**
  - Variable protections for SR operation → **Easy and Reliable design**
  - Control SR from primary controller → **No need of SR IC, low system cost**
- Accurate setting of switching frequency and dead time
  - **Simple system design**
  - **optimized system efficiency**
- Various protections
  - OTP, OLP, OCP, Latch-off Enable → **Easy system design**

Frequency Oscillator

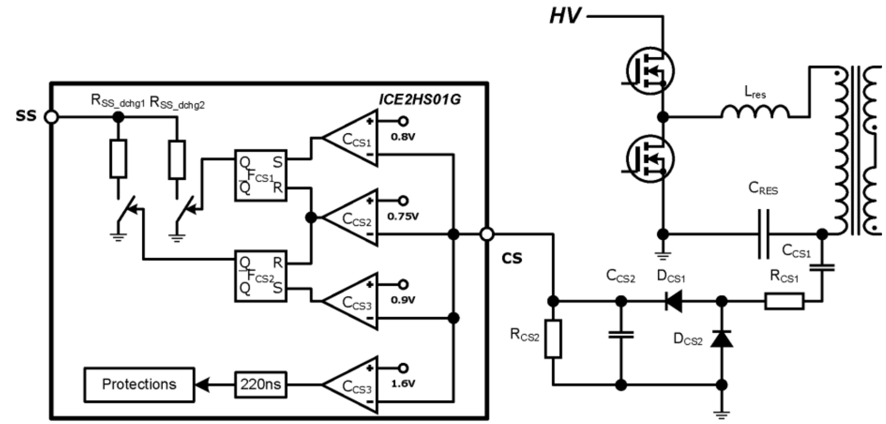
- FREQ pin is regulated at 2V constantly, the current flowing out from FREQ pin is used to charge the internal oscillator capacitor. The higher output current, the higher switching frequency

- Minimum operation frequency → R_{FMIN}
- Softstart frequency → $R_{FMIN}//R_{OCP}//R_{SS1}$
- Switching frequency during over current protections → $R_{FMIN}//R_{OCP}$
- Maximum switching frequency during no load operation → $R_{FMIN}//R_{REG}$



Current Sense and Over Current Protection (OCP)

- ICE2HS01G increases the switching frequency once an OCP is detected via CS pin
- 3-level OCP protection is implemented
  - Level 1 → switching frequency increase
  - Level 2 → switching frequency rapid increase
  - Level 3 → IC enters into latch protection

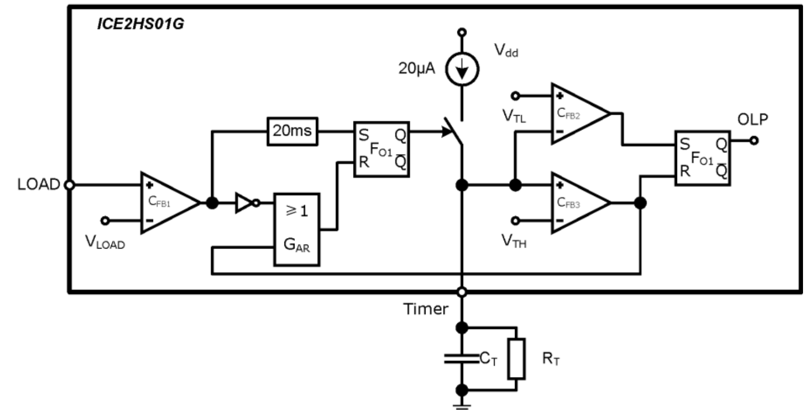


SR Control Scheme

- On time prediction and adaptive control
  - Using primary switching frequency, input bus voltage information and preset on time period to determine the on time
  - Using current sensing information for adaptive on time adjustment

Over Load Protection (OLP)

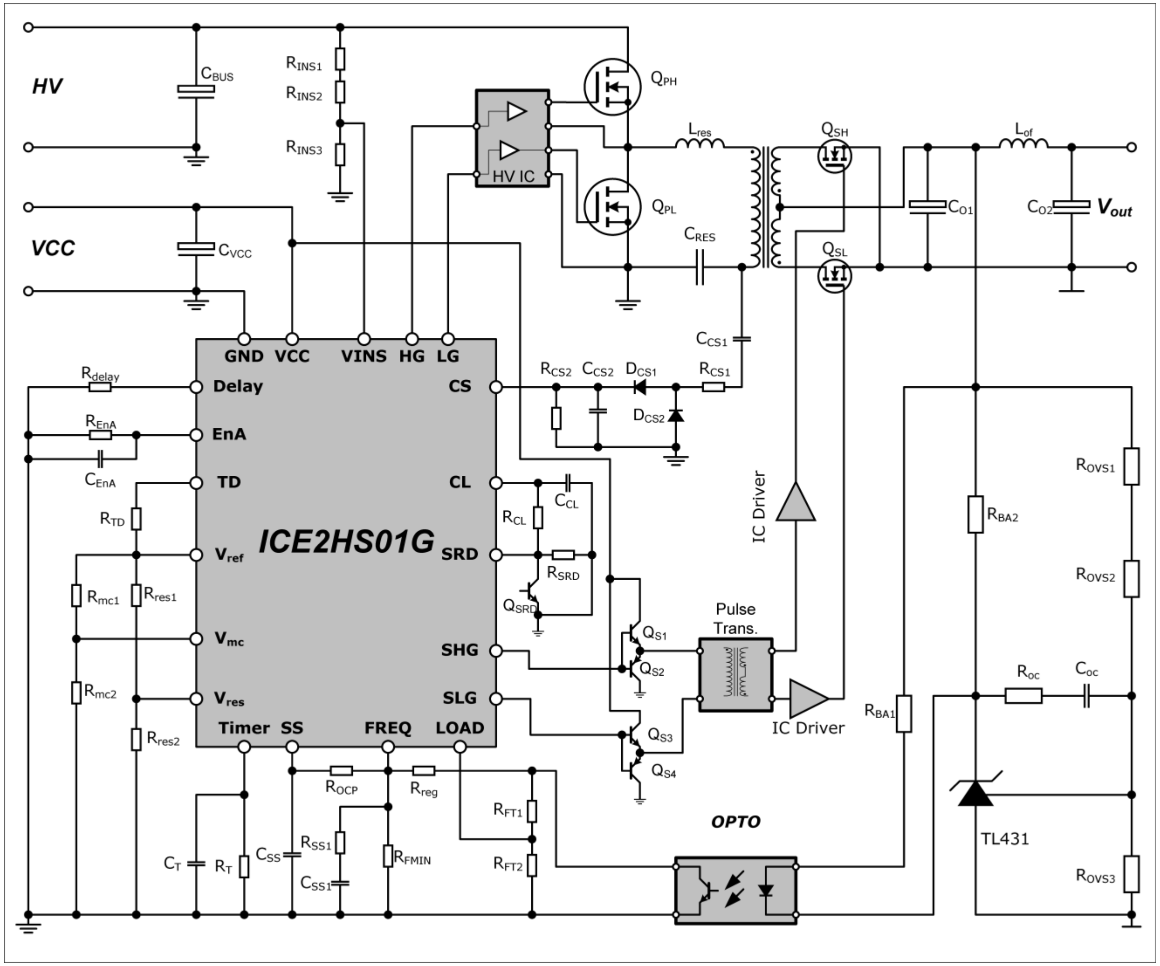
- Over load protection is detected same as open loop protection, when feedback signal is high.
- After 20ms and after timer pin reaches V_{TH}, IC enters into OLP and stop all switches and stop the charging current on Timer pin as well.
- IC will wait until the voltage on Timer pin falls below than V_{TL} , then will restart with soft start.



Burst Mode Operation

- Light load is detected when feedback signal is low.
- ICE2HS01G has two options for light load operation
  - High switching frequency as normal operation (disabled burst)
  - Enter into burst mode operation (enabled burst, limited max frequency)

Pin Layout & Typical Application Circuit



Pin Number	Pin Name
1	Timer
2	EnA
3	SS
4	LOAD
5	FREQ
6	Delay
7	TD
8	Vmc
9	Vref
10	Vres
11	VINS
12	CS
13	CL
14	SRD
15	GND
16	SLG
17	SHG
18	LG
19	HG
20	VCC

Package → PG-DSO-20-45

Reference Design #1
Solar Micro-Inverter LLC DC-DC stage

Solar LLC DC-DC stage

Full-Bridge LLC w/ Full-Bridge rectifier

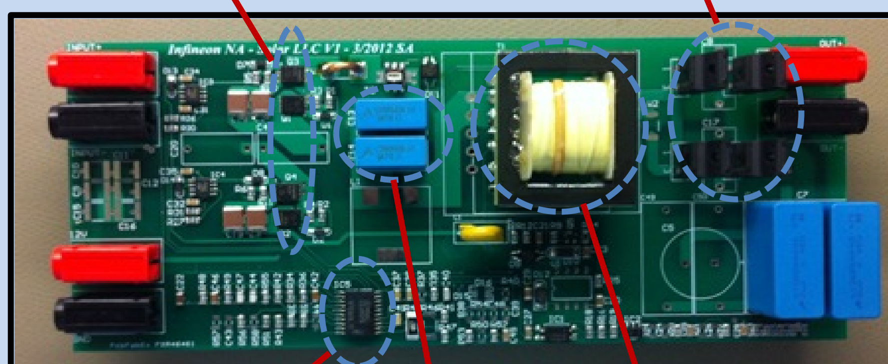
Vo	400V
Vin	16V - 36V
Vin_nom	33V
Po_max	250W @ Vin=36V
Output power derates linearly with input voltage Ex: Output power= 125W @ Vin=18V	
fr	110kHz
fmin	50kHz
fmax	190kHz
Transformer turns ratio	1:12
Cr	0.94uF
Lr	2.3uH
Lm	12.2uH

Bridge FETs

- *BSC028N06NS 60V 2.8mΩ*
- *New Generation*
- *55% reduction in Figure of Merit (Qg)*
- *37% reduction in Figure of Merit (Qoss)*

Rectifier diodes

- *IDH05G65C5 SiC 650V 5A*
- *Low voltage drop*
- *Low capacitive charge*
- *High surge current capability*
- *Improved thermal performance*

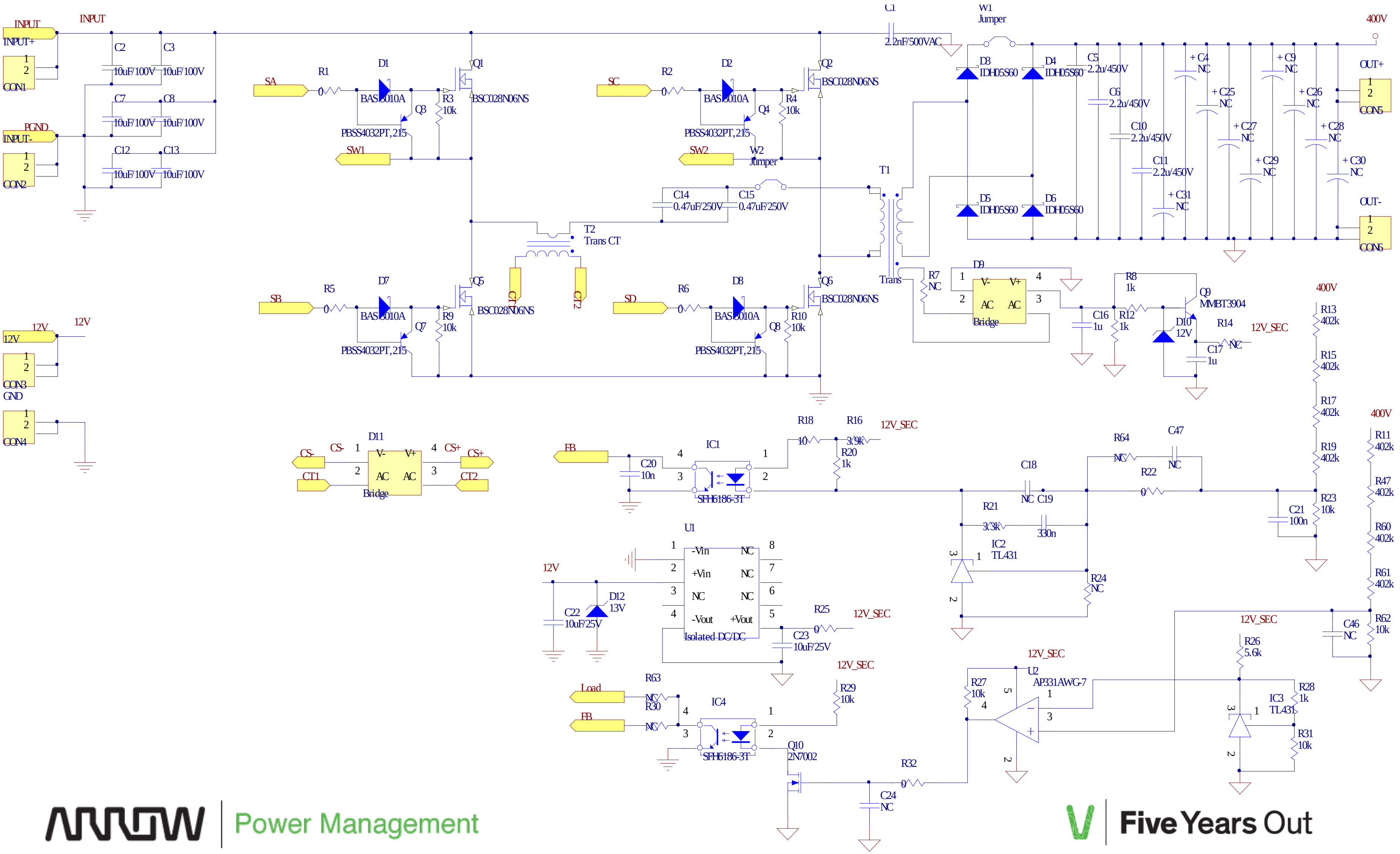


LLC analog controller
ICE2HS01G

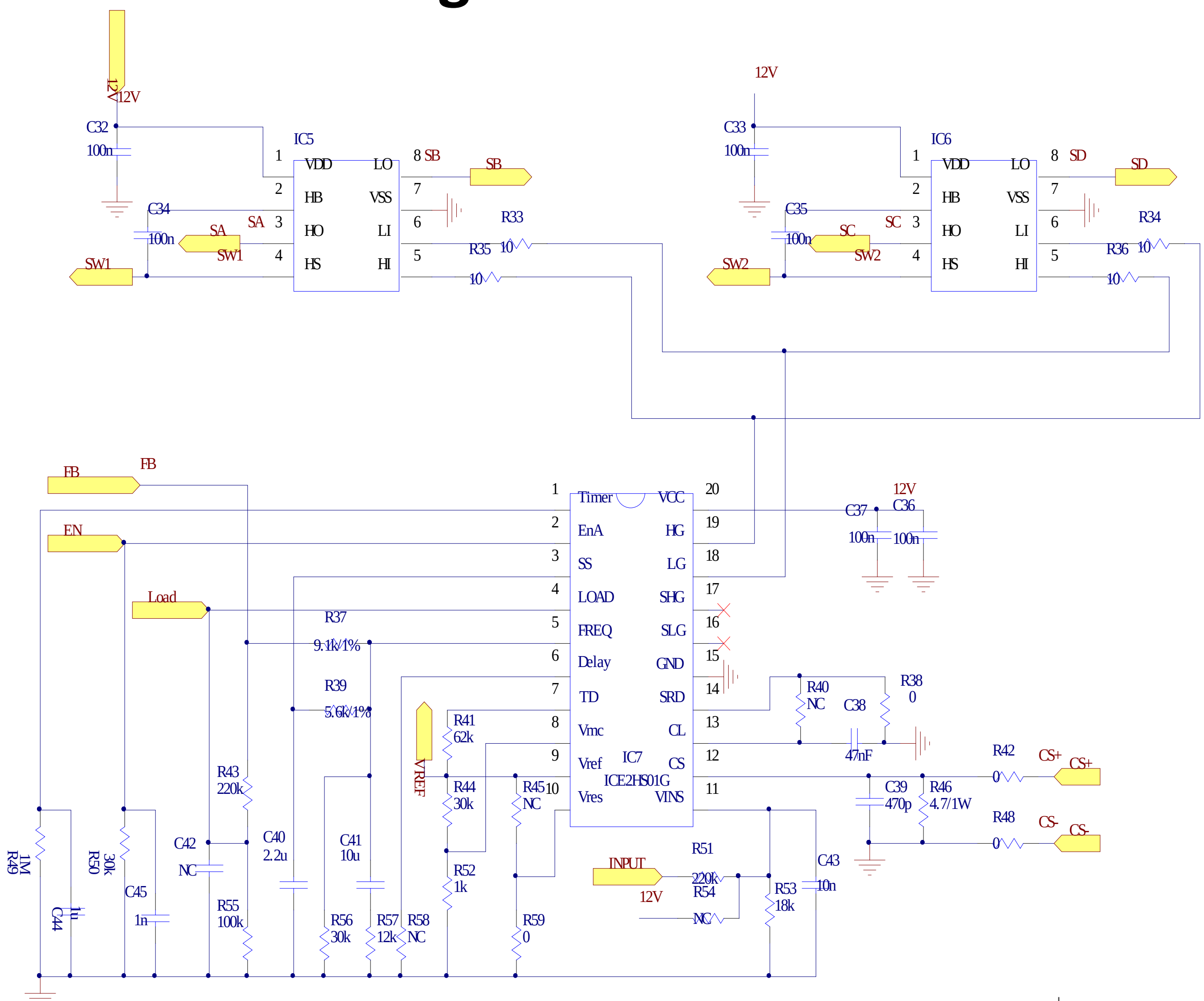
Resonant capacitor
Film MKP

Transformer/ Resonant inductor
E41/17/12

Solar LLC DC-DC stage

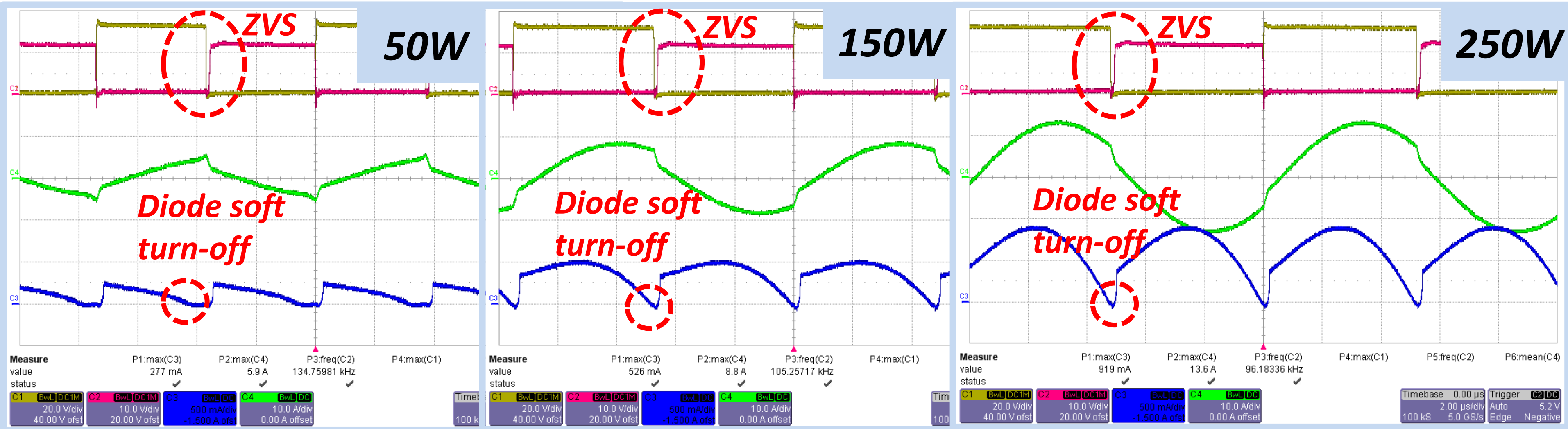


Solar LLC DC-DC stage



Experimental Waveforms
At Resonance Operation *fs=fr*

Vin= 33V



Red: *Primary FET V_{gs}*

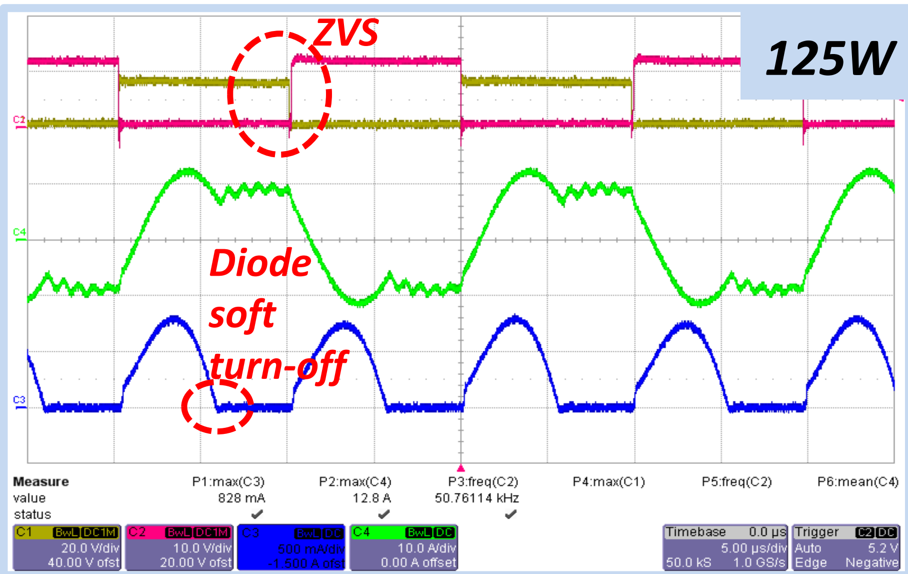
Yellow: *Primary FET V_{ds}*

Green: *Resonant current I_{Lr}*

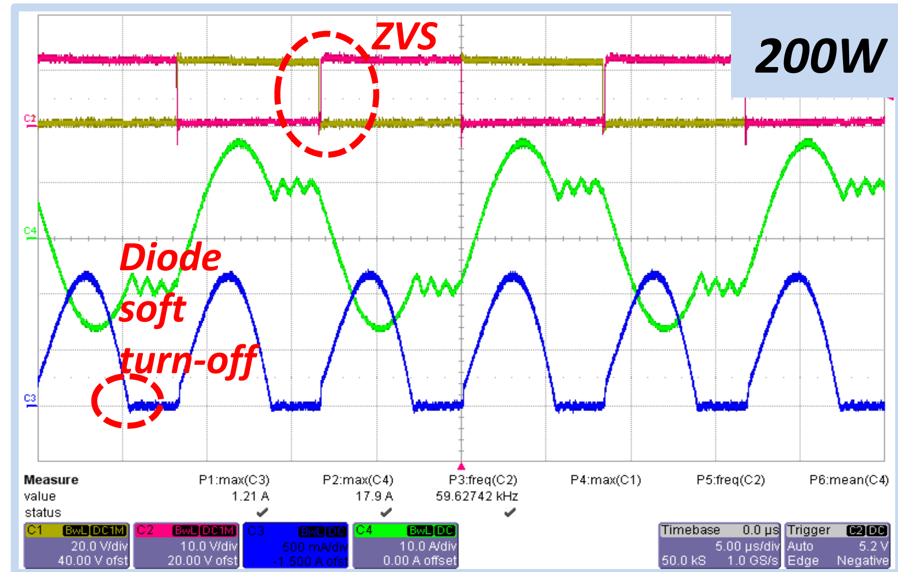
Blue: *Rectifier output current $I_{D1}+I_{D3}$*

Experimental Waveforms
Below Resonance Operation *fs<fr*

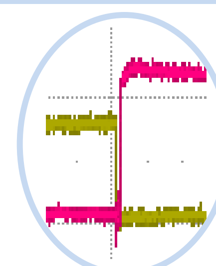
Vin= 16V



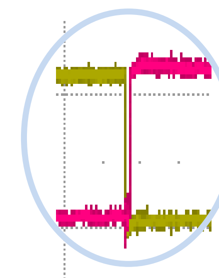
Vin= 24V



Red: *Primary FET V_{gs}*
Yellow: *Primary FET V_{ds}*
Green: *Resonant current I_{Lr}*
Blue: *Rectifier output current $I_{D1}+I_{D3}$*



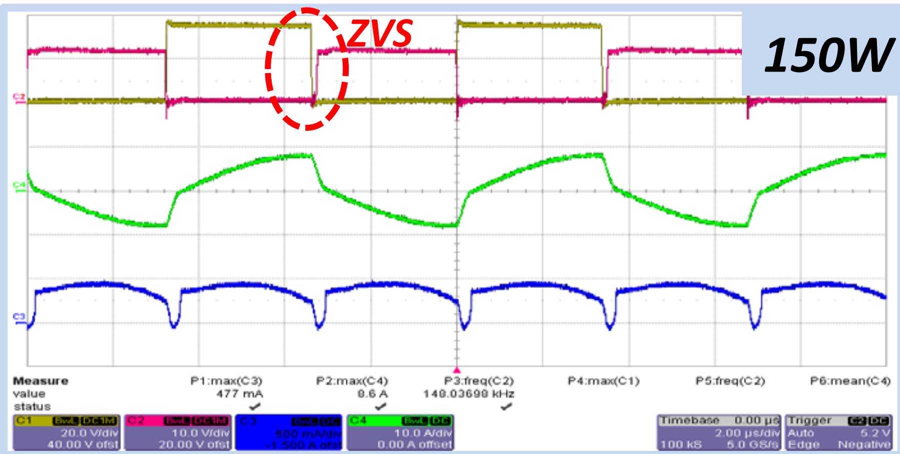
ZVS@16V

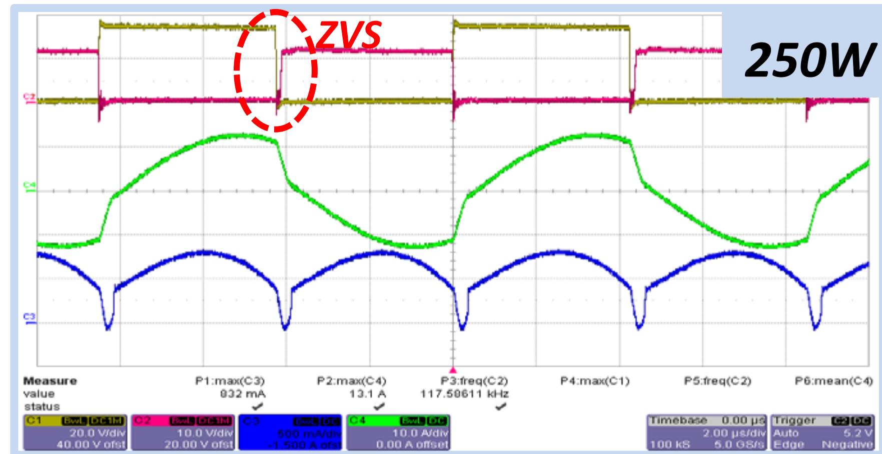


ZVS@24V

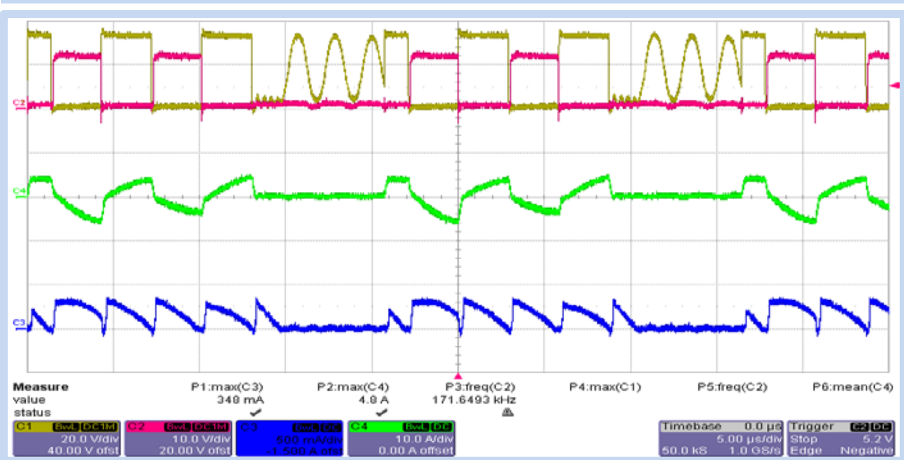
Experimental Waveforms
Above Resonance Operation *fs>fr*

Vin= 36V





Light Load Missing Cycle Mode



Red: *Primary FET V_{gs}*

Yellow: *Primary FET V_{ds}*

Green: *Resonant current I_{Lr}*

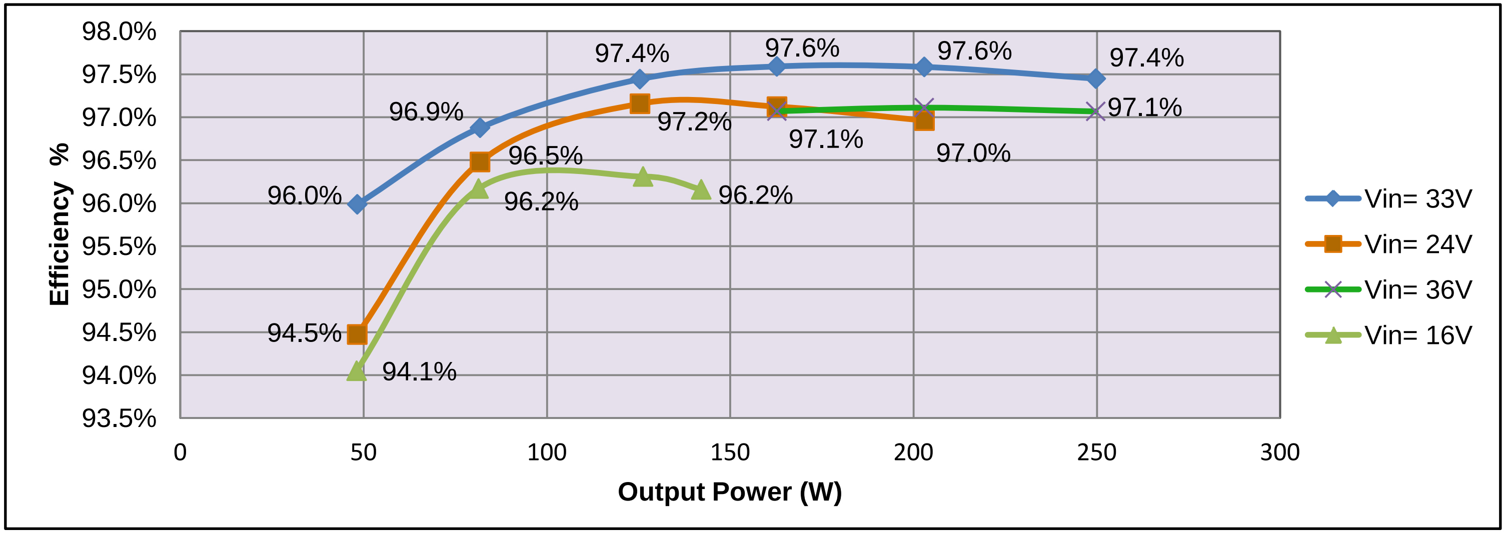
Blue: *Rectifier output current $I_{D1}+I_{D3}$*

Five Years Out

Efficiency

Input Voltage	Output Power (% of 250W)				
	20%	40%	60%	80%	100%
36V	97.1% **	97.1%**	97.1%	97.1%	97.1%
33V	96.0%	97.2%	97.6%	97.6%	97.4%
24V	94.5%	96.8%	97.1%	97.0%	
16V	94.0%	96.3%	96.2%		

*** Missing cycle mode / Burst mode operation*



Reference Design Example #2
SMPS LLC DC-DC stage

SMPS LLC DC-DC stage

Full-Bridge LLC w/ Full-Bridge rectifier	
Vo	12V/25A
Vin	315Vdc~420Vdc
Vin_nom	400V
Po_max	300W
fr	85kHz
fmin	30kHz
fmax	180kHz
Transformer turns ratio	16:1
Cr	66nF
Lr	53uH
Lm	690uH

Primary MOSFET: IPA60R199CP

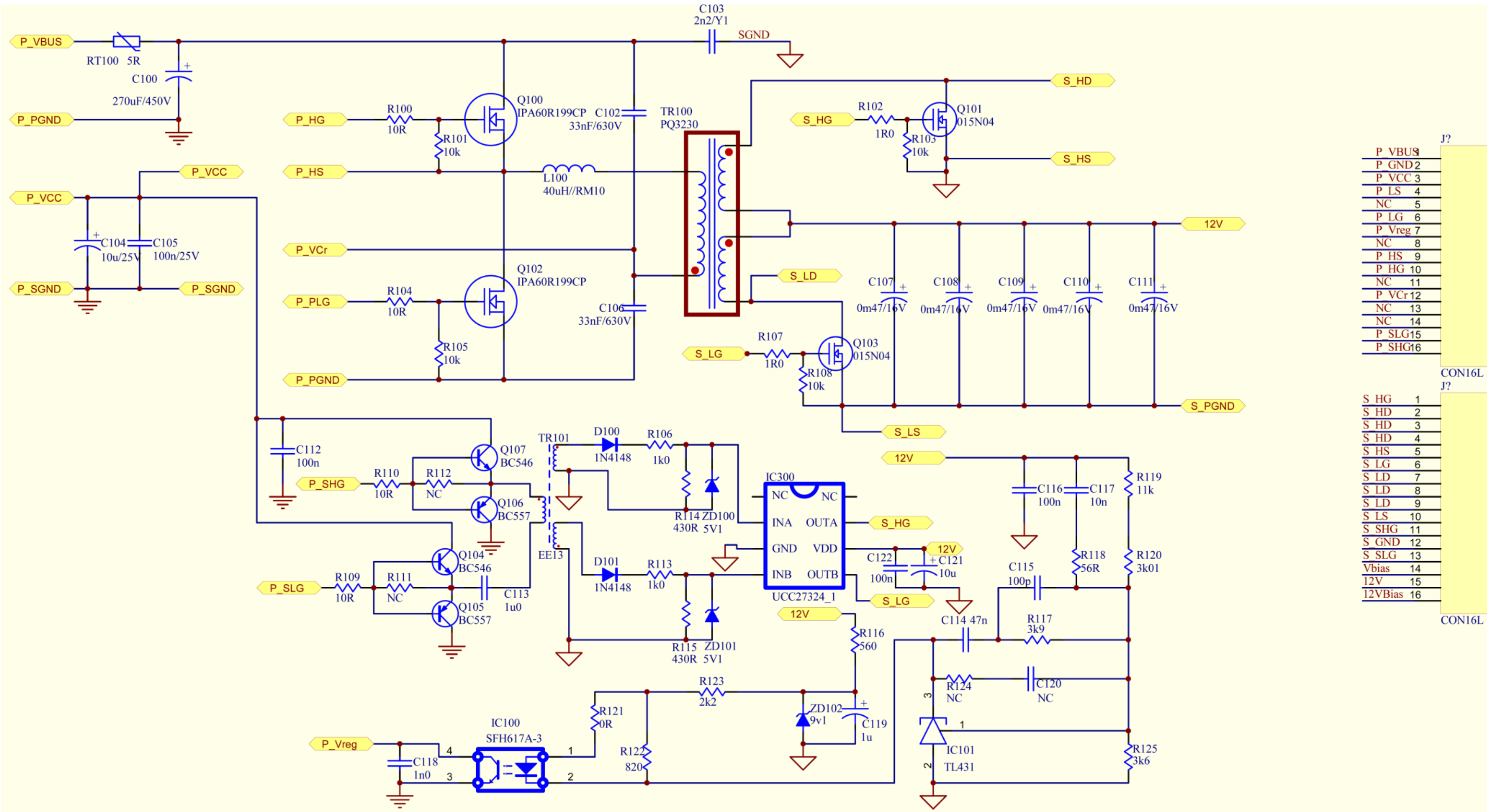
Secondary SR MOSFET: SPP015N04N G

Main Tran.: PQ3230 PC95

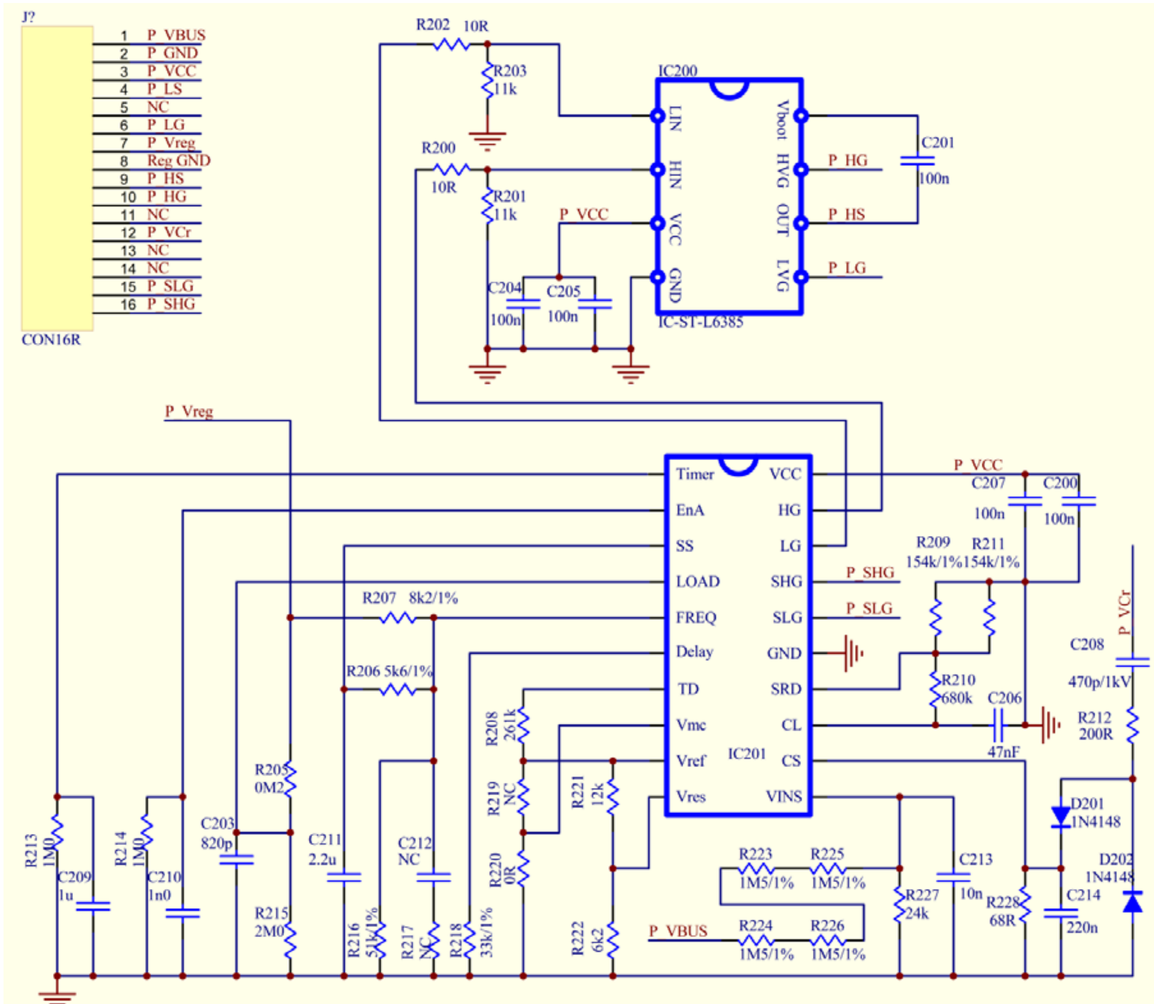
Resonant Choke: RM10 PC95

Pulse Tran.: EE13 PC44

SMPS LLC DC-DC stage

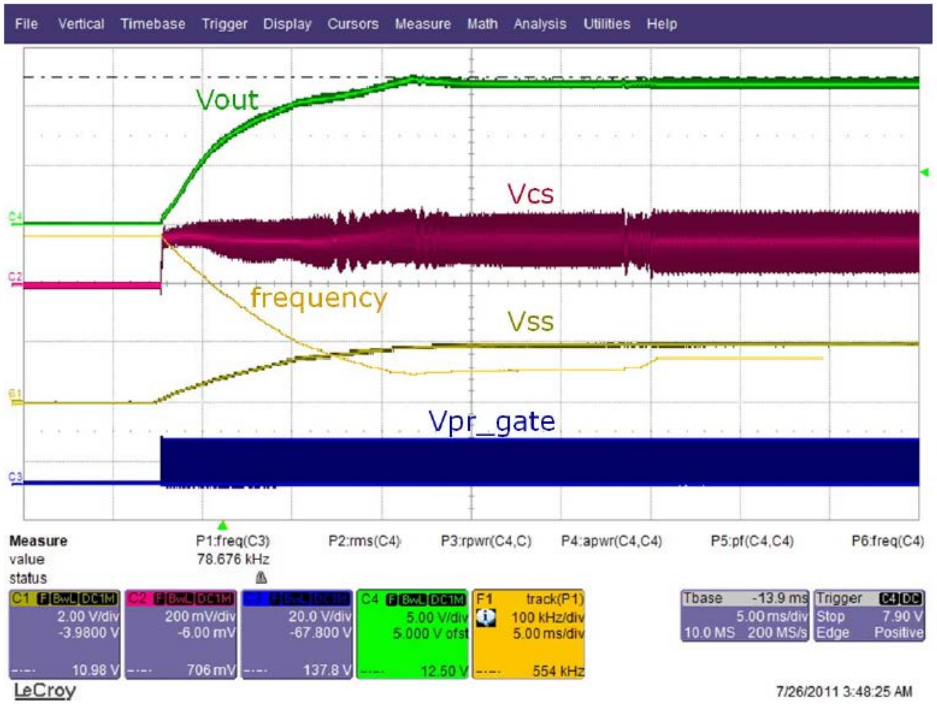


SMPS LLC DC-DC stage

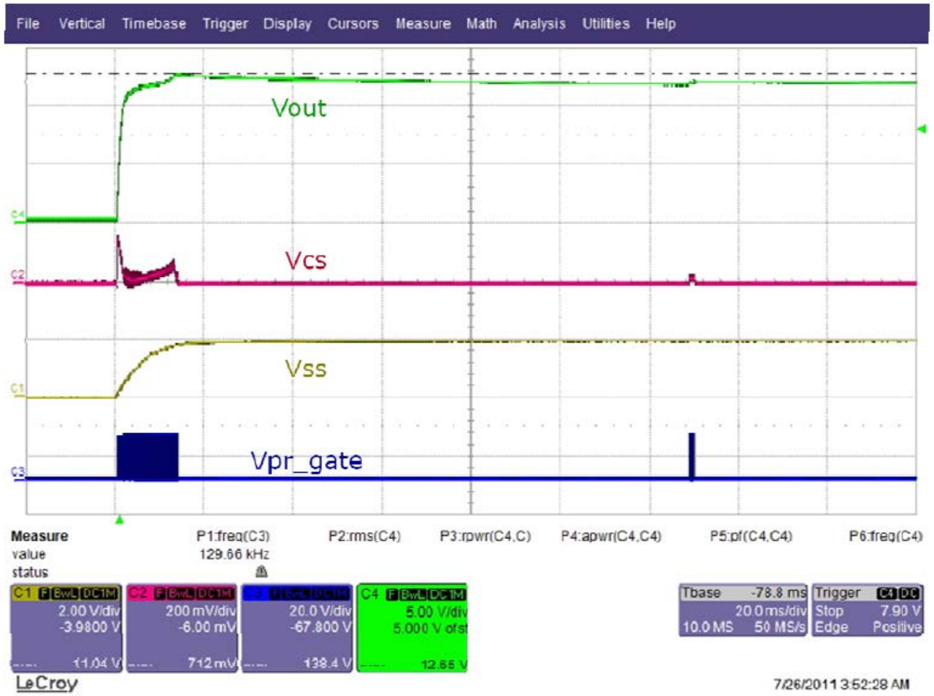


Soft Start

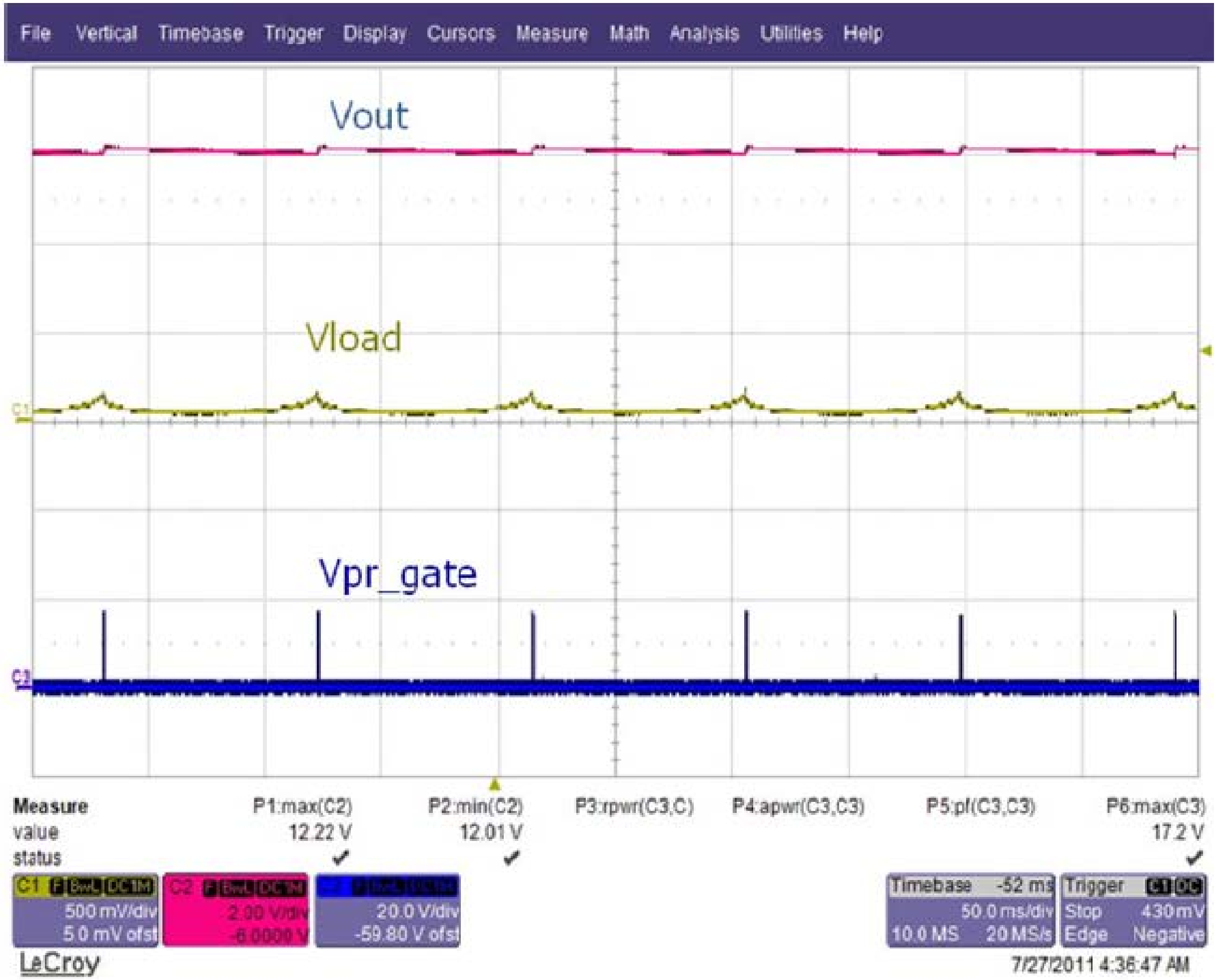
Full load



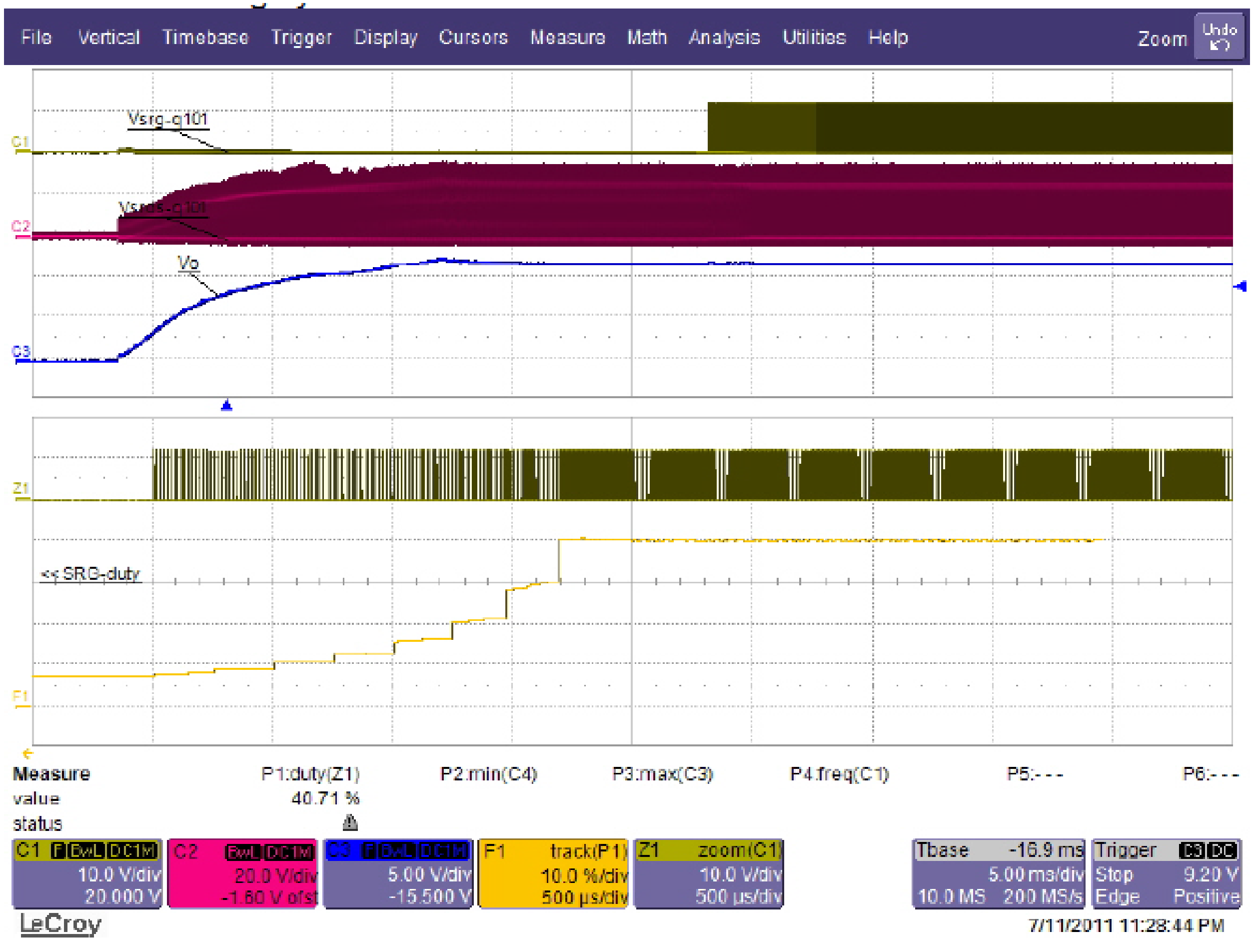
No load



Burst Mode Operation at No Load

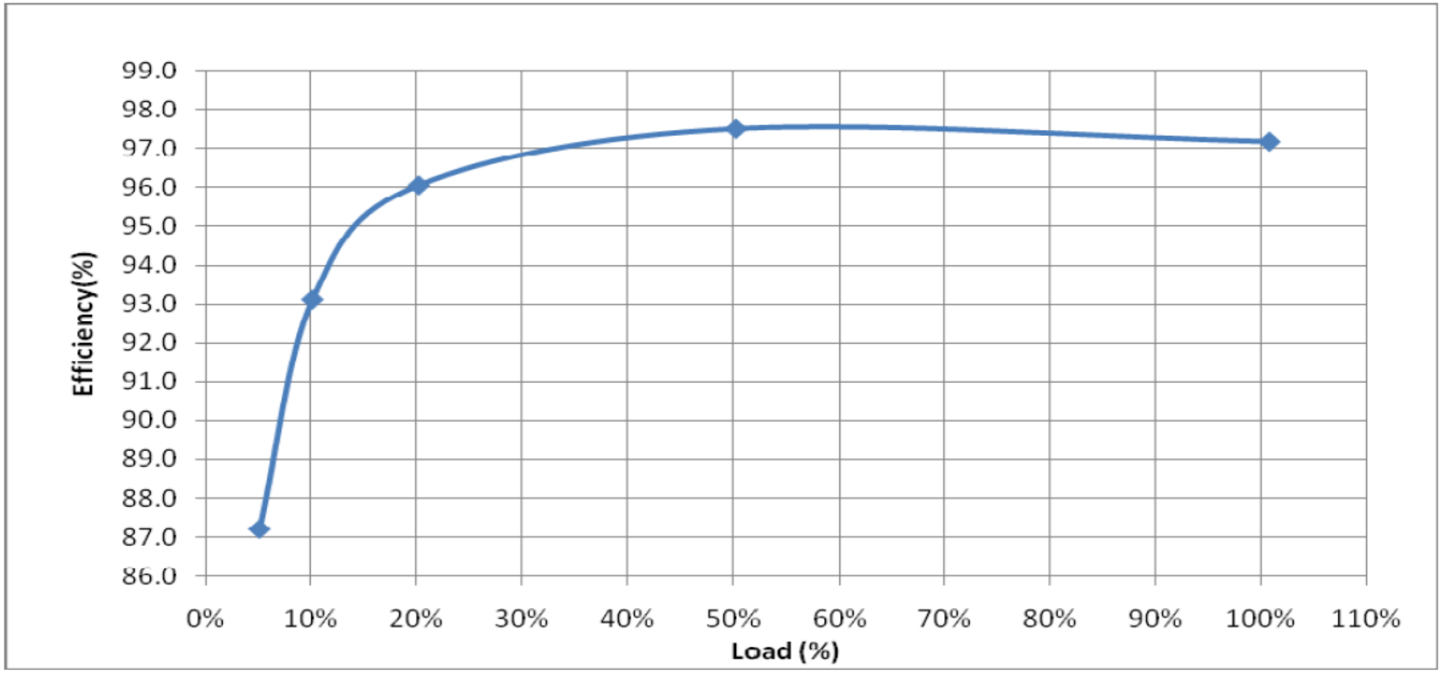


SR Soft Start at Full Load



Efficiency

V_{out}(V)	I_{out}(A)	P_{out}(W)	Load(%)	V_{in}(V)	I_{in}(A)	P_{in}(W)	Vcc(V)	Ivcc(A)	Pvcc(W)	Eff.(%)
12.17	1.25	15.21	5%	399.99	0.04	17.06	15.00	0.03	0.375	87.2
12.17	2.49	30.31	10%	399.89	0.08	32.17	15.00	0.03	0.375	93.1
12.17	4.98	60.59	20%	399.77	0.16	62.70	15.00	0.03	0.375	96.1
12.16	12.41	150.95	50%	399.34	0.39	154.46	15.00	0.03	0.375	97.5
12.16	24.87	302.42	101%	399.22	0.78	310.84	15.00	0.03	0.375	97.2



References

1. 300W LLC Evaluation Board with LLC controller ICE2HS01G. Application Note.
2. Resonant LLC Converter: Operation and Design. Application Note.
3. Design Guide for LLC Converter with ICE2HS01G. Application Note.
4. LLC Converter Design Note.
5. High Performance Resonant Mode Controller. ICE2HS01G datasheet.


Application Note, V1.1, August 2011

EVAL-2HS01G-300W

300W LLC Evaluation Board with LLC controller ICE2HS01G

Power Management & Supply

Infineon

Never stop thinking.


Application Note AN 2012-09
V1.0 September 2012

Infineon

Resonant LLC Converter: Operation and Design

250W 33Vin 400Vout Design Example

Sam Abdel-Rahman

Infineon Technologies North America (IFNA) Corp.

www.infineon.com

Thank You

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